LIGHTWEIGHT AND TRANSPARENT DOMES

Izis Salvador Pinto

Abstract
Domes have existed for centuries, from ancient domed structures such as igloos to contemporary domes such as the Eden Project. However, over the years there has been a gradual shift in construction of long-span domes, from the use of opaque and heavy materials, to the use of transparent and lightweight structures. The development in material technology provides the opportunity to reduce the weight of materials and structures to be lightweight and high-strength, saving energy, fuel, and contributing to the low carbon agenda. The progress in materials science and the evolution in the technology of construction and manufacturing in architecture make the utopian ideas of the past into a reality. Domes with Ethylene tetrafluoroethylene (ETFE) cushions as cladding system are lightweight and transparent structures. ETFE is a cost-effective, environmentally friendly material. The advantages of ETFE, compared to glass, is that ETFE is one per cent of the weight of glass, transmits more light and costs far less to install. Furthermore, this material does not degrade under ultraviolet light and is unaffected by atmospheric pollutants. This paper presents an overview of contemporary long-span domes constructed with lightweight materials, from the domes in buildings, to the possibility of achieving large city-dome enclosures.

Keywords
ETFE cushions, transparent dome, lightweight structures, design process, community service.

Introduction
Ancient domes were made of mud, stone, masonry, timber and brick, but since the nineteenth century, the predominant materials used for building domes were reinforced concrete, steel, fabrics, glass and plastics. There is a trend towards lightweight materials and structures for building and construction based on progress in materials technology. Parallel to progress in material sciences, the mechanics of materials have also evolved markedly. While the first domes worked in compression only, most of the recent structures combine tension and compression. In compression, the material does not utilize the yield limit and is an inefficient use of resources. Tension is the most efficient use of material because the load bearing capacity is independent of the length and it depends only on the material properties and cross-sectional area. Optimized long-span domes are based on the balance between tension and compression and the use of lightweight materials.

A Lightweight structure is defined by the optimal use of material to carry external loads, or pre-stresses. Material is used optimally within a structural member if the member is subjected...
to membrane forces rather than bending' (Bletzinger and Ramm, 2001). The more load a structure can carry with least self weight the more efficient it is.

Evolution in the Construction of Domes

Most landmark domed buildings feature some major technological innovation which allowed architects and engineers to achieve longer span structures.

Pre-Industrial Revolution Domes
A remarkable dome of the early architecture is the dome of the Pantheon in Rome (see figure 1) which was built between 118 and 125 Before Christ under Emperor Hadrian, with a span of 43.3 meters. It was constructed with a very strong concrete made of pozzolana cement. The most important problem during the construction was the massive weight of the dome. In order to support it, the thickness of the walls gradually decreases as the height increases and at the top of the dome it has been used a lighter type of concrete. The thickness of the dome varies from 6.4 metres at the base of the dome to 1.2 metres around the oculus. Furthermore, the use of coffers in the ceiling and the oculus of 9.1 metres in diameter also reduce the weight of the dome. The dome’s oculus lightens the load and acts as a compression ring. It has always been open to the weather, allowing rain to enter and fall to the floor, where it is carried away through drains. The Pantheon remains the largest unreinforced concrete dome ever constructed.

The Pantheon was the largest dome until Brunelleschi’s dome at Santa Maria del Fiore (see figure 2) in Florence was constructed. The

Brunelleschi’s dome was built between 1420 and 1436 After Christ and has a diameter of 44 meters which is more than the diameter of the domes of St. Peter’s Basilica in Rome and St. Paul’s Cathedral in London. Even today, Brunelleschi’s dome remains the largest brick dome ever constructed.

Post-Industrial Revolution Domes
Since the Industrial Revolution, many new building materials have been invented. Furthermore,
in the eighteenth century, mathematicians learned to apply their knowledge to the study of structures, making it possible to calculate the exact tension in any structure. Both tension and compression stresses were increasingly used to calculate structures with new materials such as reinforced concrete, glass and steel, fabric and plastics.

**Reinforced concrete domes and shell structures**

In the late nineteenth century, the reinforced concrete was created. This allowed wider spans to be constructed because reinforced concrete is able to resist tension, compression and bending. Reinforced concrete is extremely efficient in domes and shell structures. Thin concrete shells become a practical concept
in 1924, when Walther Bauersfeld, employed by the Zeiss Corporation, designed a semi-elliptical shell with 16 metres in diameter based on a steel structure geodesic dome in Jena, Germany.

The Kresge Auditorium (see figure 3) designed by Eero Saarinen and constructed in 1955, is a reinforced concrete shell structure supported only on three points. The shell is one-eighth of a sphere with a 49 metres span and a height of 15.24 metres. The glass curtain walls are the cutting planes which gives the sphere three flat edges. The thickness of the concrete shell is 8.9 cm and it is increased at the edge beams to 14 cm.

Thin domes of pre-stressed concrete opened new directions in domes supported merely at points rather than in the traditional constricting ring. Reinforced concrete pioneers such as Pier Luigi Nervi, Eduardo Torroja and Felix Candela introduced new design theories and construction techniques experimenting with shells of different forms.

In recent years, concrete with glass, polypropylene and steel fibres has been created. Structural analysis and design have certain principles common to all types of concrete but some variations are necessary for specific types of concrete.

**Glass and steel domes**

The development of construction methods in iron and steel was an important innovation in architecture allowing building stronger, taller and longer-span structures with less expenditure of material than stone, brick, or wood. Iron has long been utilized in building, but steel was introduced on the second half of the nineteenth century resulting in the construction of tall structures and long-span domes, bridges and space trusses. The U.S. Pavilion at Expo 67 in Montreal is a famous lightweight geodesic dome designed by R. Buckminster Fuller in 1967 world’s fair. It is a space frame of steel pipes
of 76.2 meters in diameter, enclosing a more conventional interior construction. In a fire in 1976, during routine repairs, the 1,900 acrylic panels were destroyed.

There has been a change from opaque to translucent and transparent domes. Glass has been known since early times but it was expensive. In the nineteenth century, glass has started to be used in architecture due to the mass production of glass sheets, the development of steel frames, cable structures, fixing devices and elastic and elasto-plastic sealants (Sebestyen, 2003). The use of glass and transparent materials in architecture allowed creating a visual connection between the interior space and the outside scene. Almost all glass domes are assembled from planar glass sheets. Some examples of glass architecture are the Crystal Palace, London and the Reichstag Dome (see figures 4 & 5), Berlin. The Crystal Palace was a cast-iron and barrel vaulted glass roofed building erected in London to house the Great Exhibition of 1851. It was destroyed by fire in 1936. The Reichstag Dome was designed by Norman Foster Architects and constructed in 1999. It is a steel and glass dome of 38 meters in diameter, with a spiral ramp ending in a terrace where visitors can see a 360-degree view of central Berlin.

Fabric and plastic domes

Fabric structures have historically been used in tents (Shaefier, 1996). However, only since the 1960s tensile structures have been built by engineers and architects. This kind of structure is very efficient because it functions primarily in tension. Fabrication processes of fabric structures favour curved surfaces, and most tensile structures are supported by some form of compression or bending elements, such as masts, compression rings or beams. Examples of tensile structures are the Olympic Stadium in Munich and the Millennium Dome. The Olympic Stadium in Munich was built for the 1972 Summer Olympics, designed by Günther Behnisch and Frei Otto, and was considered revolutionary for its time. It was the first time that large transparent canopies of acrylic glass were used with steel stabilizing cables. The Millennium
Dome (see figure 6) built in London in 1999 by Richard Rogers is a mast-supported, dome-shaped cable network with a diameter of 365 meters. It is the largest of its type in the world. The building structure was engineered by Buro Happold, and the entire roof structure weighs less than the air contained within the building. The roof is made of Polytetrafluoroethylene (PTFE) coated glass fibre fabric, a durable and weather-resistant plastic supported by twelve 100 metre-high towers.

Pneumatic structures can be air-supported or inflated. The air-supported structure is a dome-shaped membrane with a fixed perimeter and an interior pressure higher than the atmospheric pressure, whilst an inflated structure is a closed inflated pneumatic beam with inner pressure lower than the atmospheric pressure.

**Retractable domes**

Many sports stadiums are domed, especially in locations with extreme climates. A major improvement to the domed stadium was accomplished with the construction in 1961 of the Civic Arena in Pittsburgh, the first long-scale structure with a roof that could be opened and closed (Ishii, 2001). The dome had a diameter of 126 meters and it was the largest retractable, stainless steel dome roof in the world supported by a massive 80 meters long cantilevered arm on the exterior. The demolition was completed on March 2012.

The retractable domed roof of the Rogers Centre in Toronto has a diameter of 230 meters and was built in 1989. Another example of retractable domed roofs is the Oita Stadium constructed in 2001. It is a multi-purpose stadium with a diameter of 274 meters in Japan. The roof sections move up from the two sides along the main beam arch, meeting exactly above the roof. The stationary portion of the roof is clad in titanium while the movable roof is clad with Teflon panels. The membrane is not only lighter in weight than glass, but it has great tensile strength and is impermeable.
Etfe Domes and the Utopian Ideas

Utopian ideas

In 1962, Buckminster Fuller and Shoji Sadao proposed a bubble dome with a width of 3.2 kilometres above Midtown Manhattan (see figure 7). Fuller’s idea was that the giant transparent dome would reduce cooling costs in summer and heating costs in winter by reducing the ratio of surface to volume. Instead of having to heat or cool each building separately, the entire dome would be kept at a moderate temperature level throughout the year. The proposed structure was relatively simple, but the material needed for such a large city scale dome enclosure did not exist at that time.

Neither project was built, but was used as inspiration by the future generations of architects and engineers that with new materials and construction techniques have been able to build what in the past was seen as utopian.

ETFE cushions

Ethylene tetrafluoroethylene, ETFE, is a fluoropolymer developed as an insulating material for the space industry to resist friction and abrasion, immune to radiation, and extremely effective at both high and low temperatures. ETFE was patented by DuPont in 1940 and Tefzel is its registered trademark. Only in the 1970s, the material started to be commercialized and in 1982, Vector Foiltec pioneered ETFE cushion cladding system under the brand name of Texlon. For almost thirty years, ETFE has been used in numerous buildings and public spaces all over the world.

ETFE cushions (see figure 8) are pneumatic structures that consist of two or more layers of ETFE foil with a thickness between 100 and 200 μm, inflated with low-pressure air and restrained in aluminium extrusions supported by a lightweight structure. ETFE is used for cladding and the cushions are continually pressurised by small pumps which maintain the pressure between 250 and 400 Pa. It gives structural stability and insulation to the roof. ETFE cushions are extremely lightweight weighing between 2 and 3.5 kg/m². Furthermore, the raw material is not a petrochemical derivative and many components are fabricated from recycled material (LeCuyer, 2008).

This material does not degrade under ultraviolet light and combines exceptional light transmission with high insulation which can...
reduce winter heating costs. Each layer of foil has a transparency of between 90-95%. The amount of solar shading and the transparency of the building envelope can be modified by changing the translucency, density and number of layers. If desired, photovoltaic cells can be integrated in the cushions to create pollution-free electrical energy.

ETFE can deal with large deflections in the support structure because of its toughness, high resistance to tearing and ability to work over a 300-400% elongation range. An important fact to remember when choosing ETFE cushions for cladding is that it is acoustically transparent with a mass of less than 1 kg/m². In the case of fire, ETFE has the property of self-venting the products of combustion to the atmosphere. ETFE has the ability to self-cleanse under the action of rain due to its synclastic shape. For all of that, ETFE
cushions provide a lightweight, cost effective and geometrically flexible architectural solution with good thermal performance and high transparency.

**ETFE domes**

ETFE cushions are currently being chosen by several architects and engineers as an effective alternative to glass when constructing domes and envelopes for buildings. The utopian ideas of a city scale dome enclosure proposed by Buckminster Fuller with the Midtown Manhattan Bubble in 1962 and Frei Otto with the City in the Arctic, 58 Degrees North in 1971, can be constructed with the new lightweight and transparent material.

The Eden Project (see figure 9), an environmental complex in Cornwall designed by Grimshaw Architects and constructed by Vector Foiltec, is a lightweight structure made with ETFE cushions in 2000. The weight of the construction is less than that of the air enclosed. It has a series of intersecting geodesic domes with spans of up to 240 metres. The dome structure is divided into two layers; the outer skin is formed by hexagons and the inner layer by a triangular and hexagonal grid. The Eden Project with 30,000m² was the world’s largest ETFE project at that time and helped to increase the number of constructions using this material.

The early ETFE buildings were located in temperate regions, but recent projects have been located in places with harsh climates. One example is the Khan Shatyry Entertainment Centre in Astana, Kazakhstan. It was designed by Foster and Partners in 2010. The building is an ETFE cushion envelope with 100,000 square meters that encloses multiple buildings and an urban-scale tropical landscape. The asymmetrical anticlastic conical form of the biaxial cable net is supported at its apex by a 20 meter high inverted cone that is balanced on a 70 meter tripod mast. The circumferential steel cables resist suction and the radial cables resist positive wind pressure. The net is anchored to a perimeter concrete ring beam of 200 metres in diameter. The ETFE cushions change their form as the structure deflects.
One solution to the environmental challenges facing Houston, such as hurricanes, is to cover it with a mile, 1.6 kilometres, geodesic dome. The project is called the Houston Dome and also aims to shift the costs for air conditioning and temperature control of buildings. Glass would be too heavy to build the Houston Dome, and for this reason the use of ETFE cushions was proposed because of its lightweight properties.

Another city dome scale project with ETFE cushions is the Walker Lake Dome Project (see figure 10) in Westwood, California. It is an oblate ellipsoidal and geodesic dome that encloses the town with a diameter of 6.4 kilometres, 183 meters tall at the centre and with an area of 120,774 square meters. This project can be used to provide a ground for technology to enclose and protect cities prone to weather related disasters.

Conclusion

Cladding materials have evolved a great deal in the last two centuries. Since the Industrial Revolution, most building structures are constructed of steel or reinforced concrete. Since the structure of the building is as important as the covering, both parts should be improved to the same extent.

Innovative ideas in architecture have emerged from situations with very high expectations, under pressure, and in critical and competitive circumstances. Climate change provides a very good pretext for innovation. However, architecture continues to focus on immobile structures while scientific fields like aeronautics and the automotive industry invest more in new materials and started investigating flexible lightweight structures almost a century ago.

The evolution of roofs has staggered between compression, tension and the combination of both. The dream of building long-span constructions has become reality, with the possibility of building large city-scale domes. Our constantly changing society requires more adaptable and sustainable buildings. It is crucial for the further development of architecture and engineering to investigate new materials and lightweight mobile and flexible constructions.
Lightweight and Transparent Domes

that are more energy efficient and cost effective.

The improvement in materials science, structural engineering and computer science has allowed more optimized constructions and longer-span domes. The early domes were small-diameter domes in buildings with an inefficient use of material, but actually, it is possible to construct city-dome enclosures of huge dimensions.

References


Izis Salvador Pinto
Izis Salvador Pinto received a degree in architecture and urban planning from the Polytechnic University of Valencia. She later received a Master degree in concrete engineering from the Valencia University of Civil Engineering at the department of Construction Engineering completing her Master’s Thesis about ETFE cushions at the Berlin Institute of Technology.

She has worked as an architect and urban planner in Brazil, Russia, Germany and Italy. At present, Izis is finishing a PhD in the University of Westminster at the School of Architecture and Built Environment. She can be contacted at izsalpin@hotmail.com